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Price et al.

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(54) **PERMANENT MAGNET FOR GENERATING HOMOGENOUS AND INTENSE MAGNETIC FIELD**

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(51) **Int. Cl.**
H01F 7/02 (2006.01)
G01R 33/383 (2006.01)

(52) **U.S. Cl.**
CPC ***H01F 7/021*** (2013.01); ***H01F 7/0273*** (2013.01); *G01R 33/383* (2013.01)

(58) **Field of Classification Search**
CPC H01F 7/021; H01F 7/0273; G01R 33/383
See application file for complete search history.

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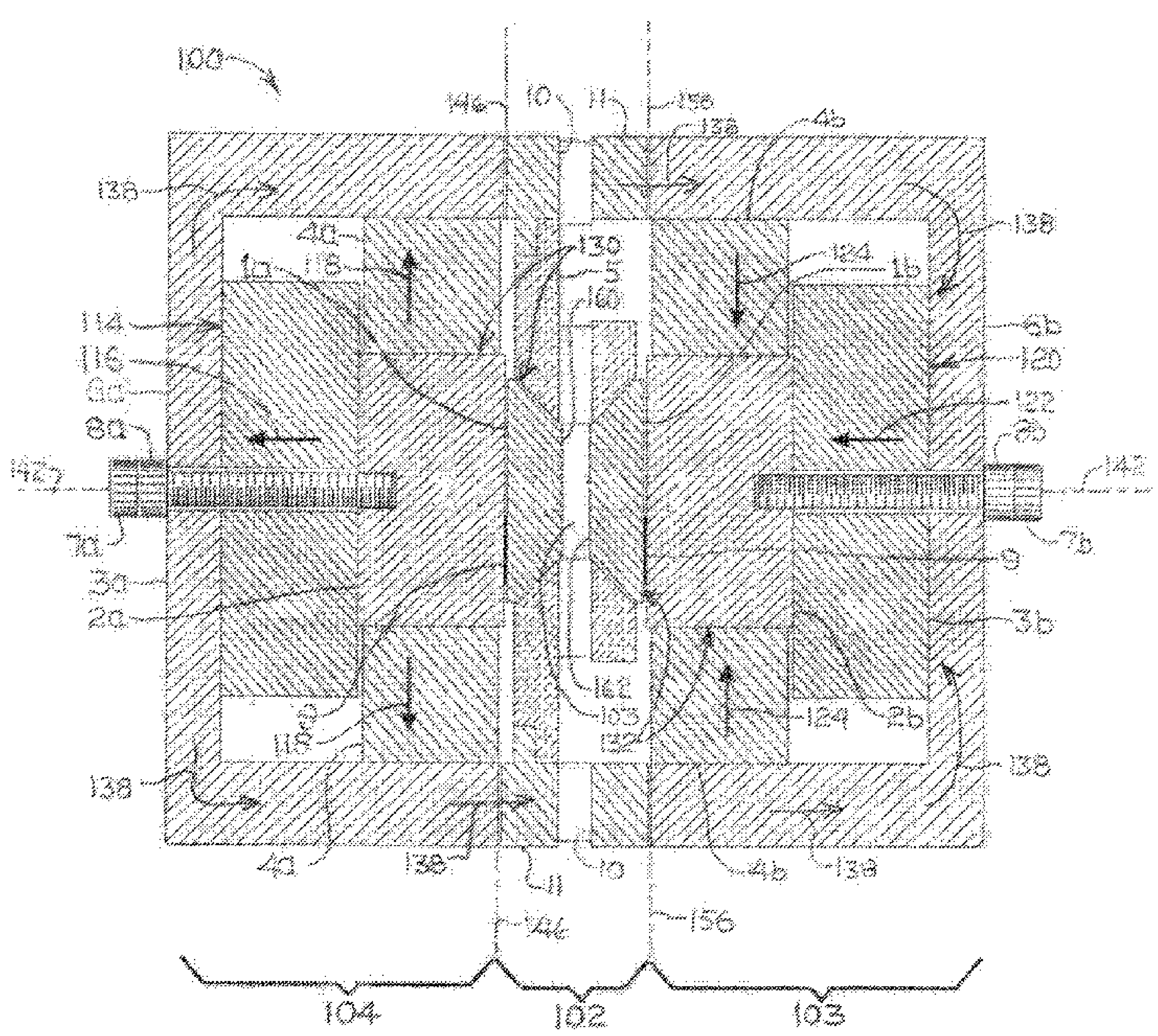
(57) **ABSTRACT**

A permanent magnet assembly for generating a homogenous and intense magnetic field includes can be adjusted for both transverse and axial gradients after completed assembly while field inhomogeneity is being measured. Gaps between pole piece bodies and pole tips are adjustable to adjust the transverse and axial gradients in a space between the pole tips.

15 Claims, 9 Drawing Sheets



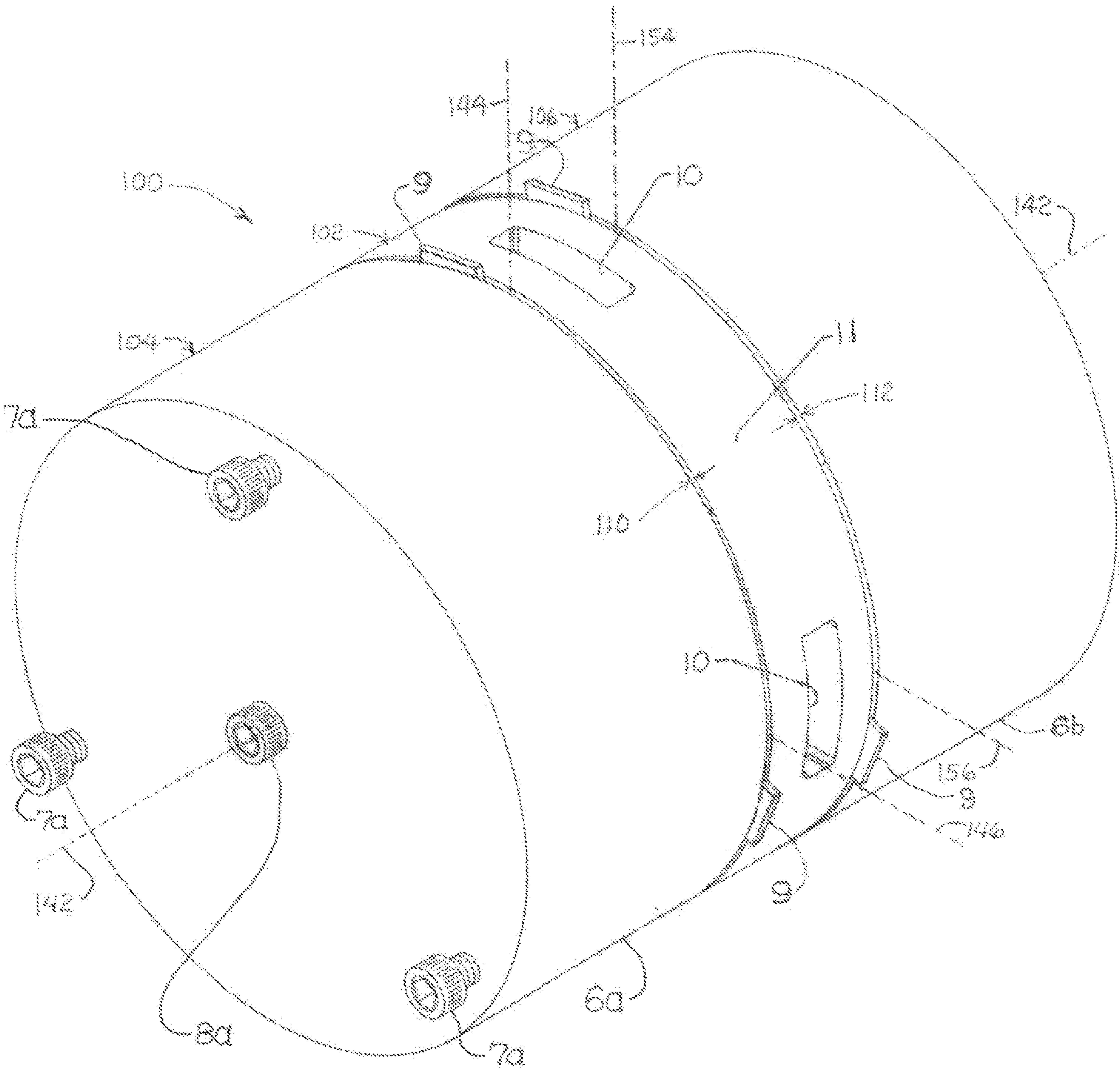

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FIG. 1

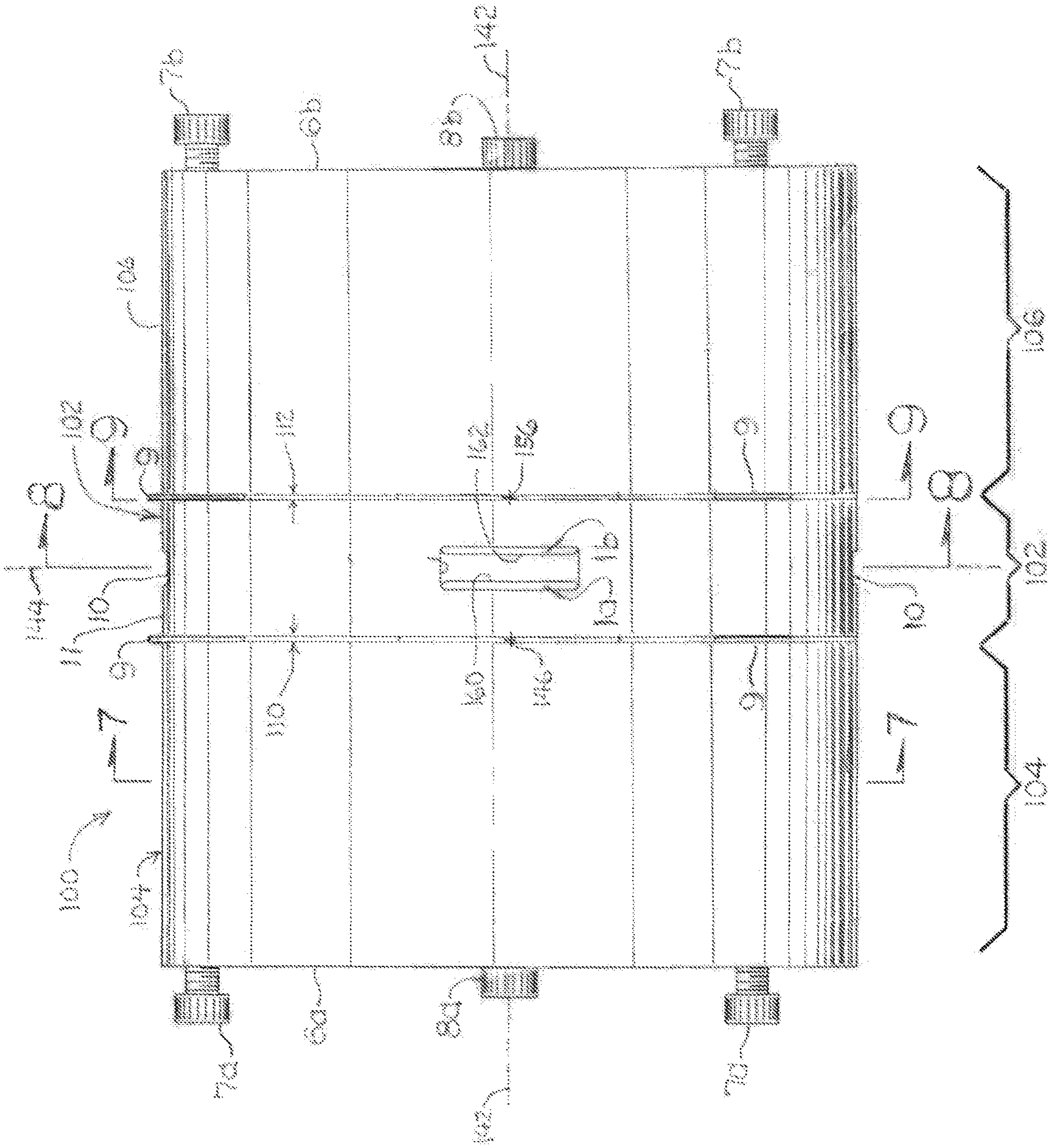
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FIG. 2

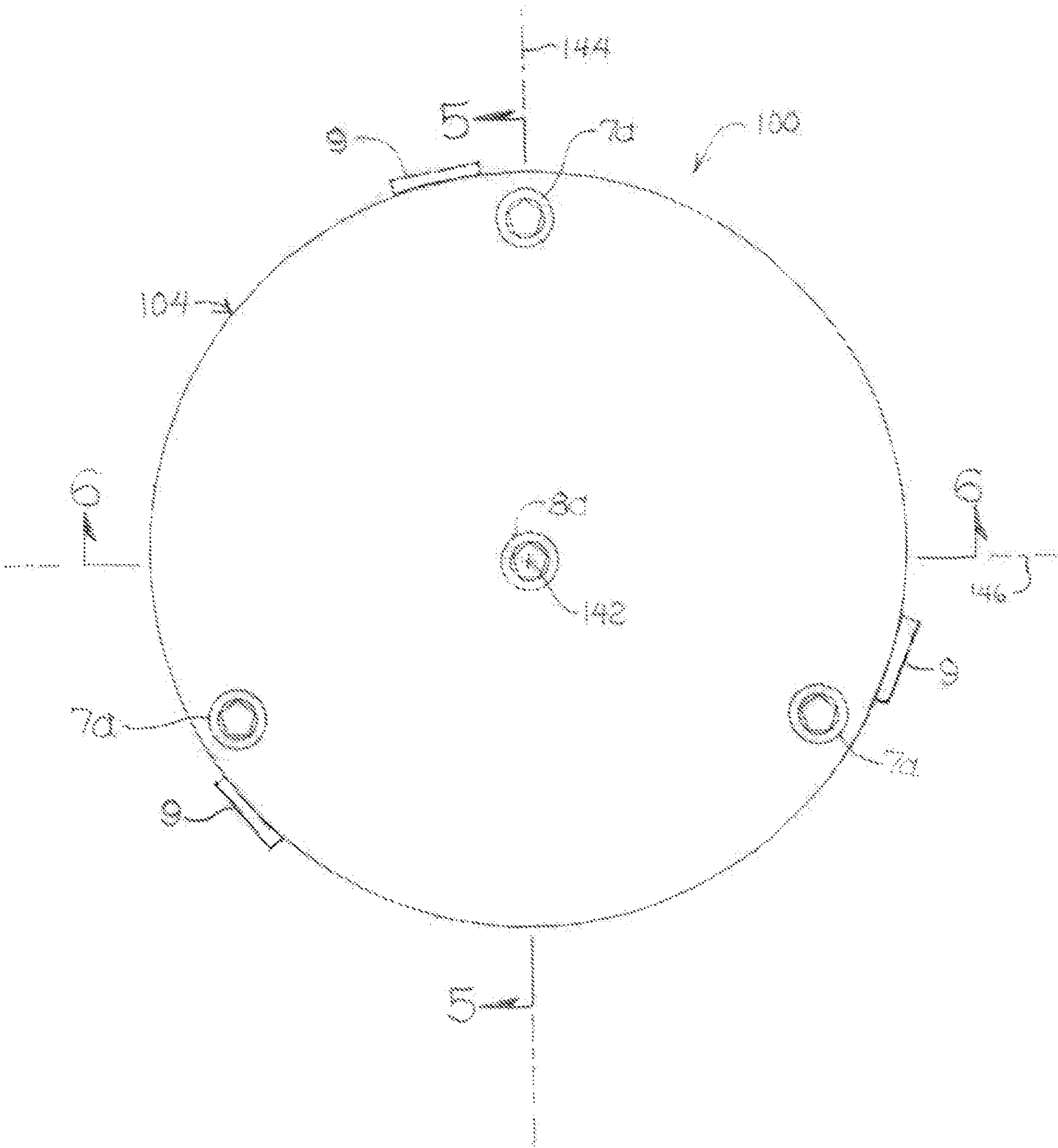

FIG. 3

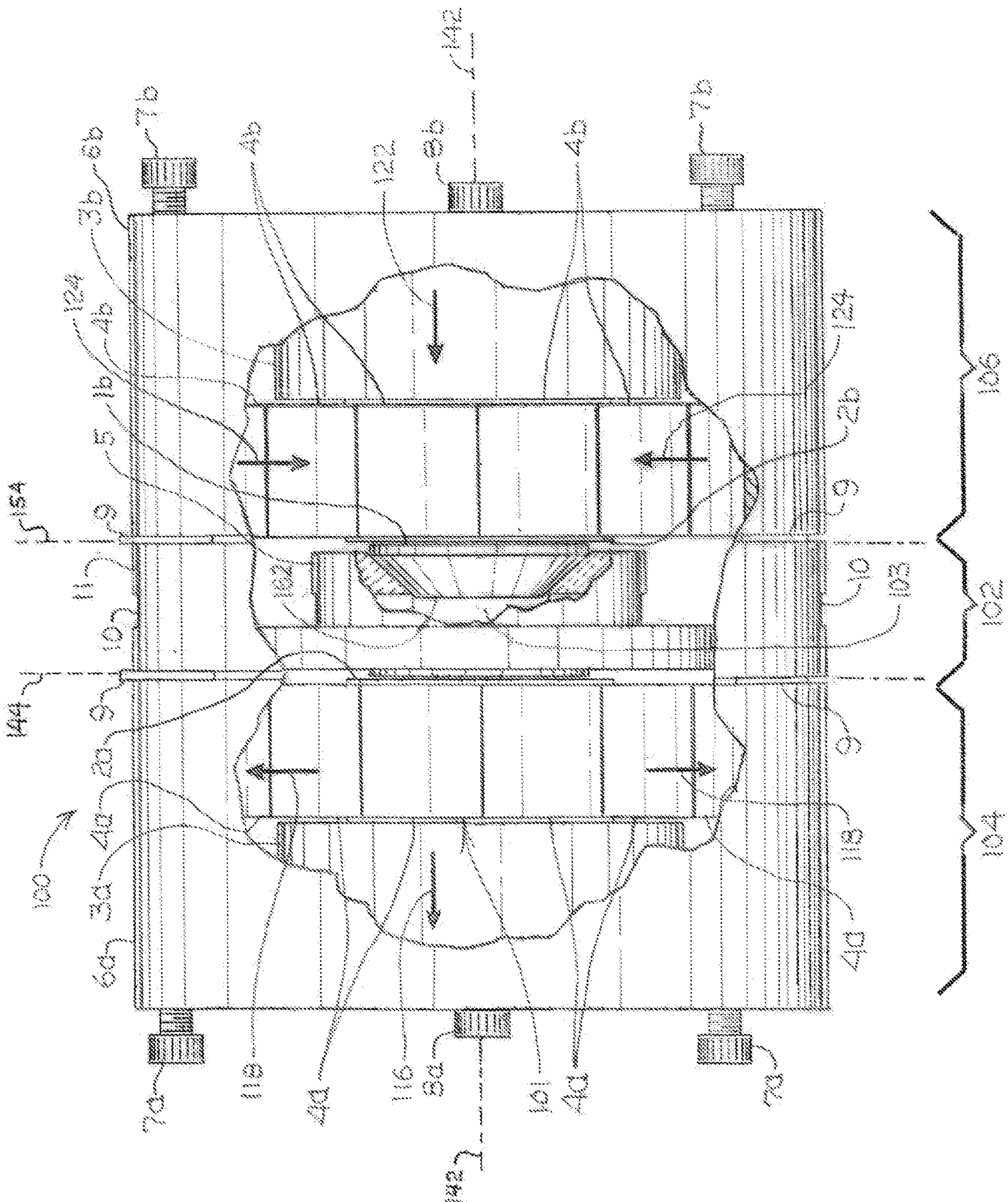

FIG. 4

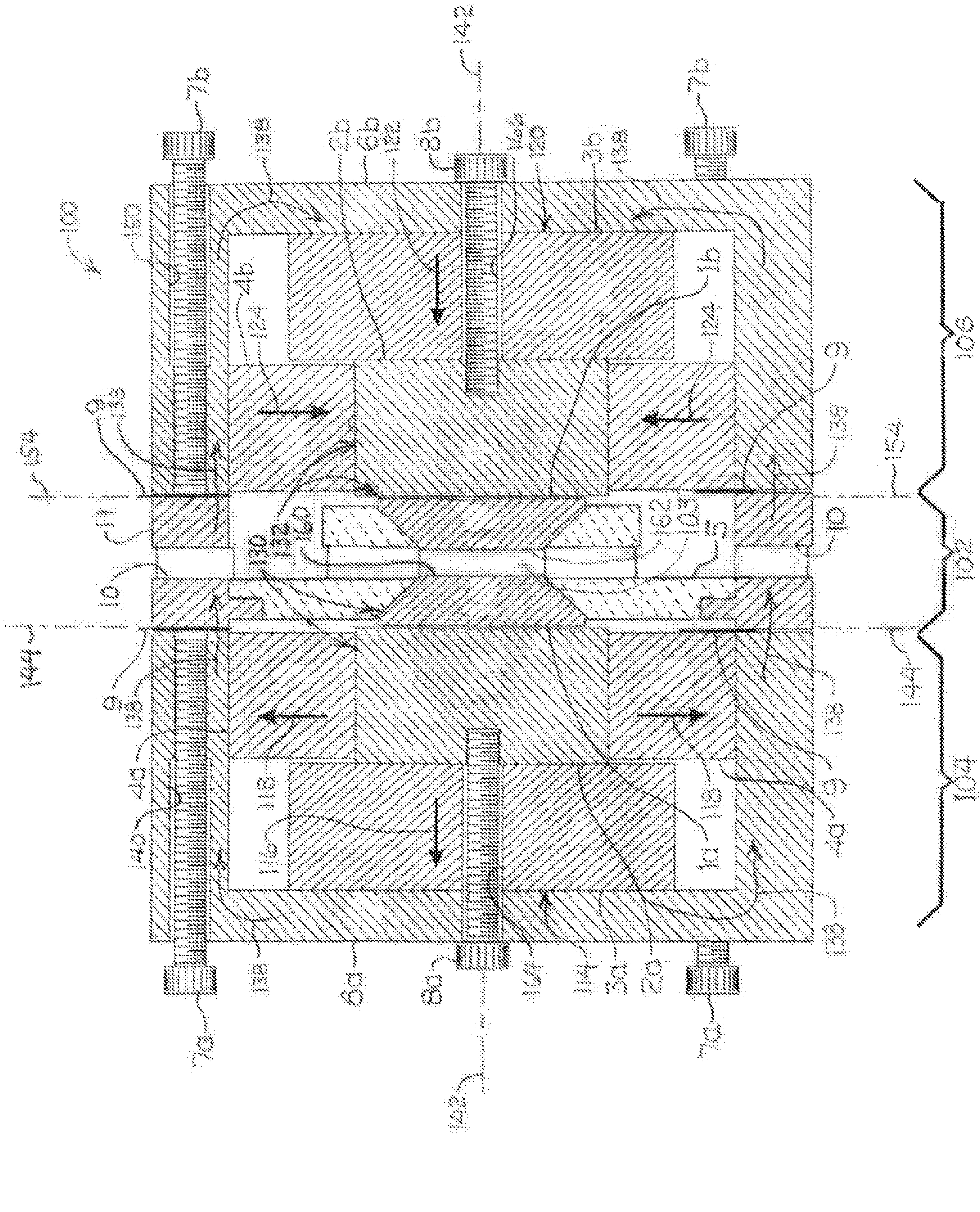

FIG. 5

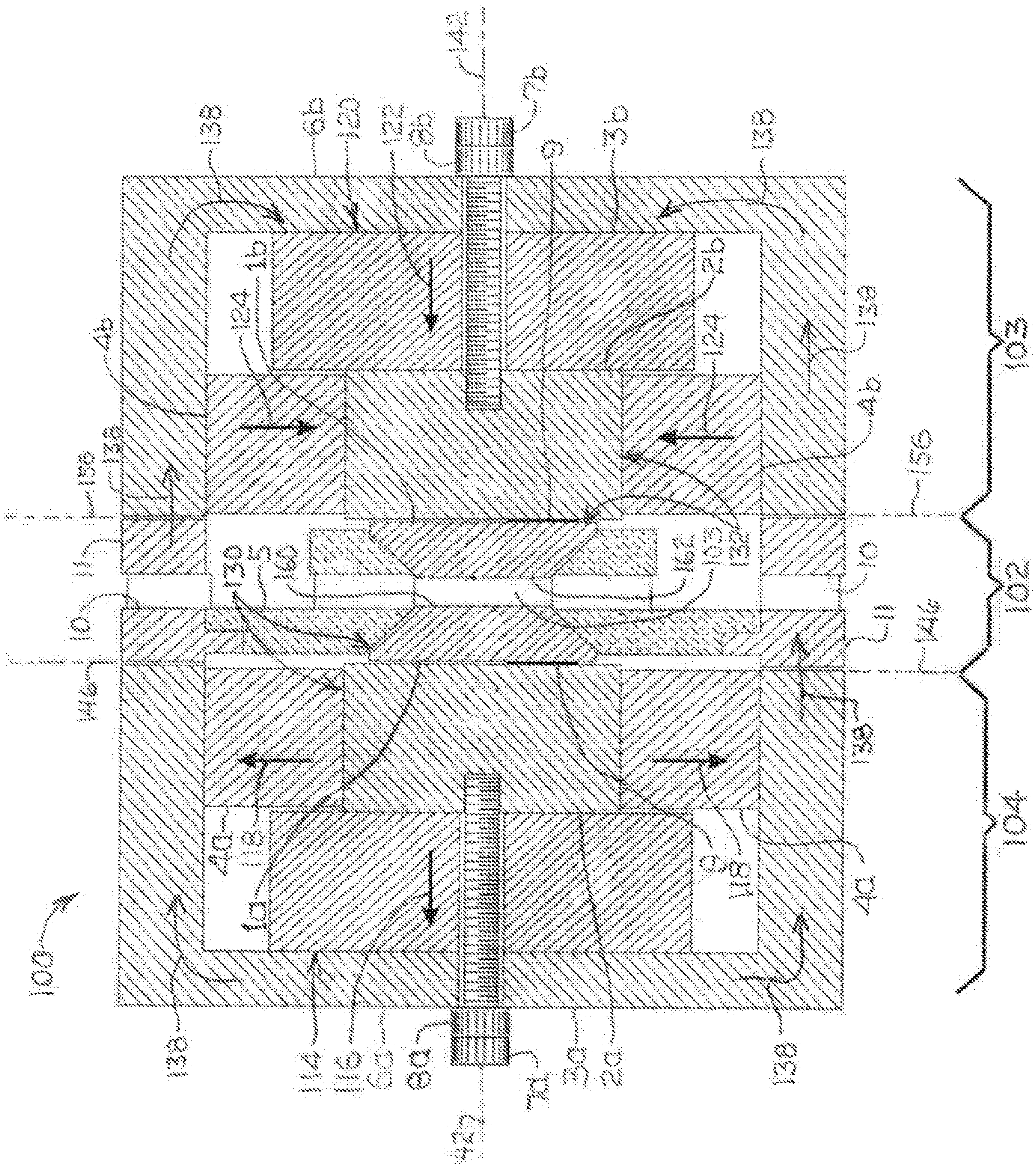

FIG. 6

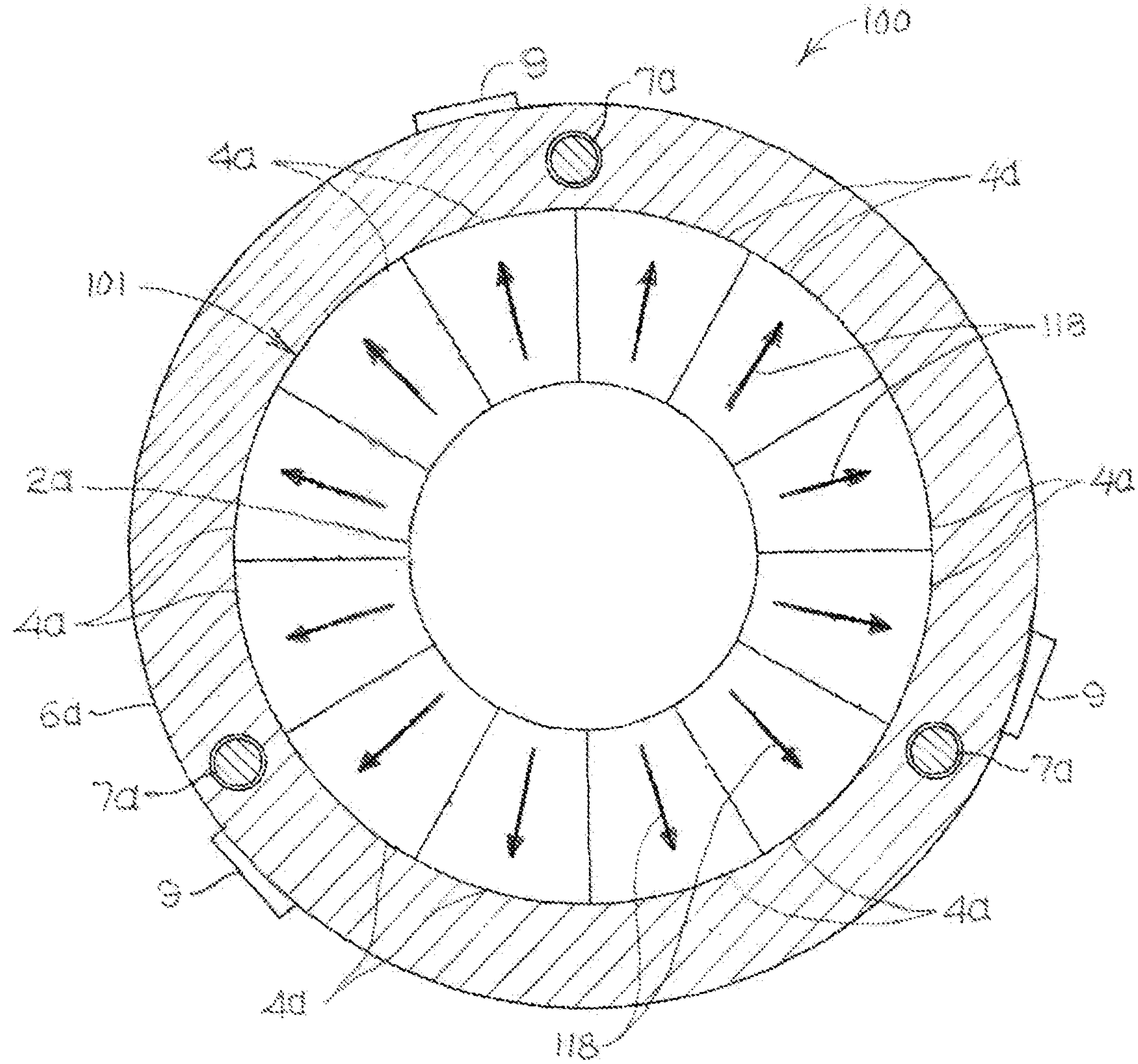

FIG. 7

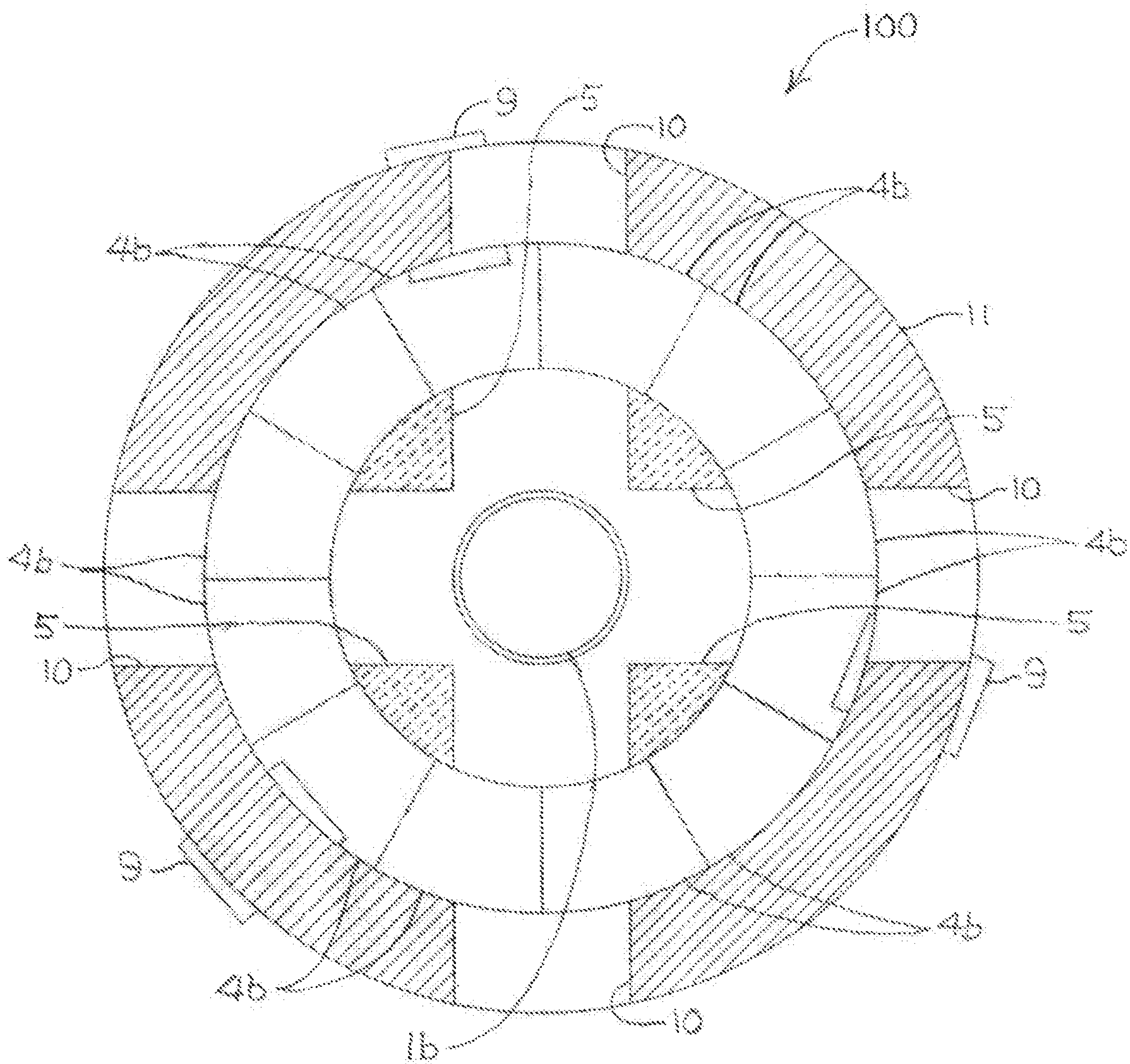

FIG. 8

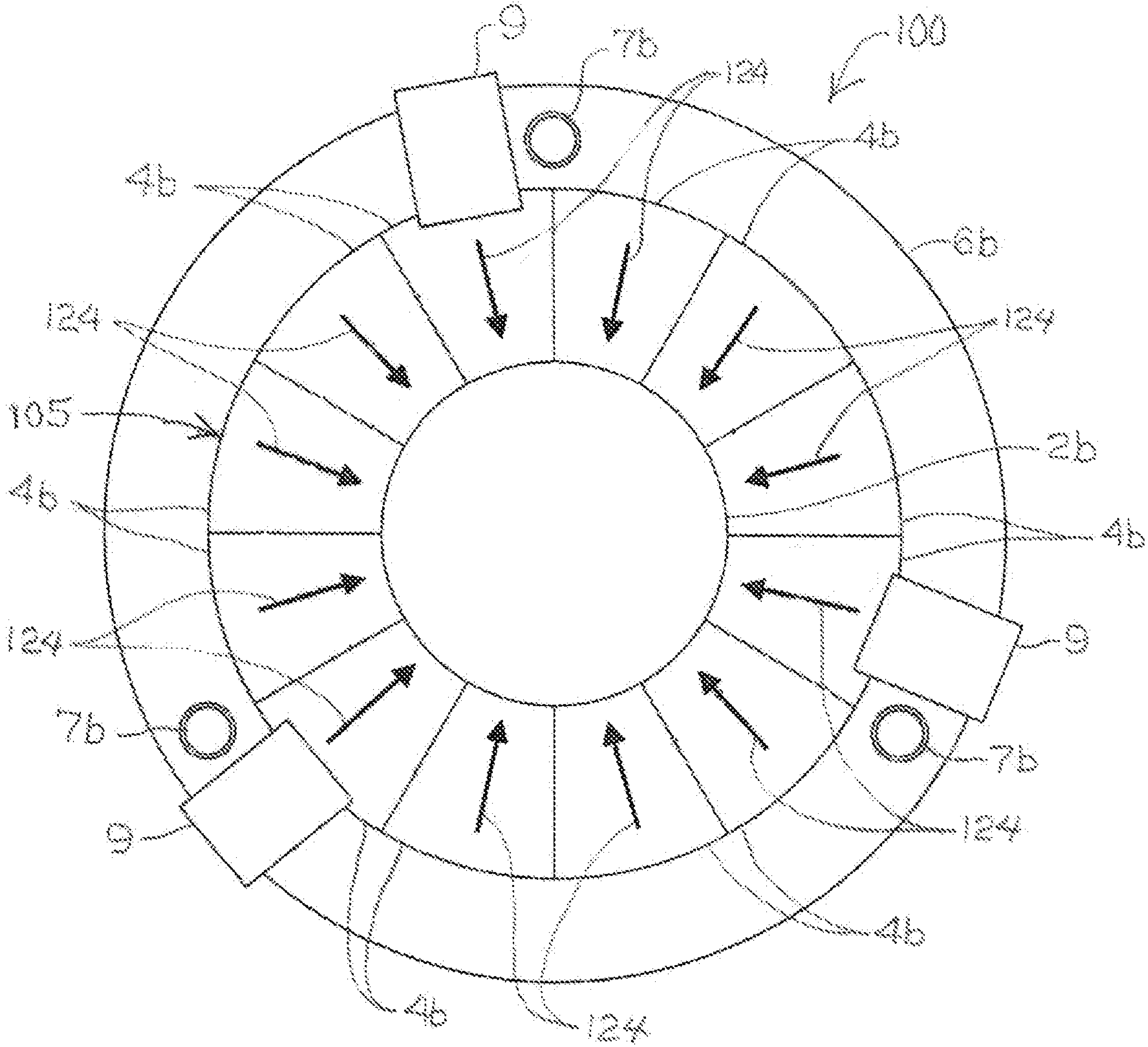

FIG. 9

PERMANENT MAGNET FOR GENERATING HOMOGENOUS AND INTENSE MAGNETIC FIELD

BACKGROUND

Technical Field of the Invention

The present invention is related to permanent magnets, and more particularly to permanent magnets for creating homogenous and intense magnetic fields.

State of the Prior Art

Magnetic fields having very high homogeneity and intensity are needed for a variety of appliances, apparatus, and processes, including, for example, nuclear magnetic resonance (NMR) spectroscopy, x-ray dichroism measurements, magneto-optical measurements, Hall effect and other electronic transport measurements, and for test and calibration of magnetic field measuring. For example, in some such applications, specifications for homogeneity may require that the root-mean-square variation of the field magnitude not exceed one part per million (ppm) over the sample volume. Also, high intensity magnetic fields are advantageous, for example, in NMR spectroscopy where both sensitivity and spectral dispersion (separation of signals corresponding to different chemical groups) improve as the magnetic field strength increases. Historically, three types of magnets have been used for these and similar applications: electromagnets, superconducting magnets, and permanent magnets. However, there are problems with each of these types of magnets.

Electromagnets capable of generating magnetic field strengths (intensities) above one tesla (T) are massive, require substantial electrical power, and usually require cooling to remove heat generated in their resistive coils. Superconducting magnets achieve the highest fields of all common laboratory magnets, but they have to be regularly filled with expensive cryogenic liquids to keep the coil temperature below the superconducting transition temperature. Alternately, they can be cooled with dedicated cryogenic refrigerators, but such systems are costly to purchase and maintain, and they require substantial electrical power. Thus both electromagnets and superconducting magnets are unsuitable for many applications, including most portable applications and most desktop instrument applications.

Permanent magnets of smaller size can provide strong magnetic fields, but, while many variations in sizes, configurations, adjustability, stability, strength, and homogeneity have been developed, a goal of providing small permanent magnets with high homogeneity and high field strength that can be adjusted for both transverse and axial gradients after completed assembly while field inhomogeneity is being measured and that then reliably maintains the strength and homogeneity has been elusive.

The foregoing examples of the related art and limitations related therewith are intended to be illustrative and not exclusive. Other limitations of the related art and other examples of related art will become apparent to those of skill in the art upon a reading of the specification and a study of the drawings.

SUMMARY

The following embodiments and aspects thereof are described and illustrated in conjunction with systems, tools, and methods which are meant to be examples and illustrative, not limiting in scope. In various embodiments and implementations, one or more problems have been reduced or eliminated, while other embodiments are directed to other improvements and benefits.

In one embodiment, a permanent magnet assembly comprises: (a) a pole tip assembly comprising two pole tips of magnetic material, disposed symmetrically with respect to a mirror plane between them, and a pole tip mount of rigid material, whereby said pole tips and pole tip mount together comprise a rigid assembly; (b) a first polarizing assembly comprising permanent magnets disposed to draw magnetic flux out of a first side of said pole tip assembly, and an enclosing magnetic flux return disposed to guide flux into a second polarizing assembly; (c) said second polarizing assembly comprising permanent magnets disposed to insert magnetic flux into a second side of said pole tip assembly, and an enclosing magnetic flux return disposed to guide flux out of said first polarizing assembly; and (d) adjusting means whereby the position of said first polarizing assembly and the position of said second polarizing assembly can be adjusted relative to the position of said pole tip assembly.

Another embodiment is a magnet apparatus that comprises: (a) a first magnet and a second magnet positioned adjacent to each other and aligned with each other in a manner that produces a magnetic flux along a longitudinal axis that extends through both the first magnet and the second magnet; (b) a first pole piece with a first pole piece face and a second pole piece with a second pole piece face, wherein the first pole piece and the second pole piece are positioned between the first magnet and the second magnet with the first pole piece face and the second pole piece face facing each other a spaced distance apart from each other in the magnetic flux along the longitudinal axis so that there is a space between the first pole piece face and the second pole piece face, and wherein there is a first gap between the first magnet and the first pole piece face and there is a second gap between the second magnet and the second pole piece face; and (c) adjusting means for adjusting the size or shape of the first gap or the second gap.

In another embodiment, a method of providing a magnetic field comprises: (a) creating a magnetic flux along an axis; (b) positioning a first pole piece comprising a first pole piece body and a first pole piece tip that has a first pole piece tip face in the magnetic flux with a first gap between the first pole piece body and the first pole piece tip; (c) positioning a second pole piece comprising a second pole piece body and a second pole piece tip that has a second pole piece tip face in the magnetic flux with a second gap between the second pole piece body and the second pole piece tip; and (d) adjusting homogeneity of the magnetic flux in the space between the first pole piece tip face and the second pole piece tip face by varying the first gap or by varying the second gap or by varying both the first gap and the second gap.

In addition to the example aspects, embodiments, and implementations described above, further aspects, embodiments, and implementations will become apparent to persons skilled in the art after becoming familiar with the drawings and study of the following descriptions.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated herein and form a part of the specification, illustrate some, but not the only or exclusive, example embodiments and/or features. It is intended that the embodiments and figures disclosed herein are to be considered illustrative rather than limiting. In the drawings:

FIG. **1** is an isometric view of an example magnet assembly that is adjustable for both transverse magnetic gradients and axial magnetic gradients;

FIG. **2** is a side elevation view of the example magnet assembly of FIG. **1**;

FIG. **3** is a left end elevation view of the example magnet assembly of FIG. **1**;

FIG. **4** is a side elevation view of the example magnet assembly similar to FIG. **3**, but with portions of the flux return sections cut away to reveal internal components of the polarizing assemblies and the pole tip assembly, a portion of which is also cut away to reveal a pole piece tip mounted in the pole tip assembly;

FIG. **5** is a cross-section view of the example magnet assembly taken along the cutting plane line **5-5** in FIG. **3**;

FIG. **6** is a cross-section view of the example magnet assembly taken along the cutting plane line **6-6** in FIG. **3**;

FIG. **7** is a cross-section view of the example magnet assembly taken along the cutting plane line **7-7** in FIG. **2**;

FIG. **8** is a cross-section view of the example magnet assembly taken along the cutting plane line **8-8** in FIG. **2**; and

FIG. **9** is a cross-section view of the example magnet assembly taken along the cutting plane line **9-9** in FIG. **2**.

DETAILED DESCRIPTIONS OF EXAMPLE EMBODIMENTS

An example magnet assembly **100** shown in FIG. **1** is adjustable for both transverse magnetic gradients and axial magnetic gradients in a robust and stable manner to provide and maintain high homogeneity and high field permanent magnets as explained in more detail below. The example magnet assembly **100** comprises a first polarizing assembly **104** and a second polarizing assembly **106** axially aligned with each other on opposite sides of a pole tip assembly **102**. The two polarizing assemblies **104**, **106** are spatially adjustable in relation to each other and in relation to the pole tip assembly **102** for adjusting the transverse magnetic gradients and the axial magnetic gradients in a space **103** between interfacing pole piece tips (not shown in FIG. **1**) in the pole tip assembly **102**, as will be explained in more detail below. A plurality of jack screws **7***a* in the first polarizing assembly **104** are adjustable in a manner that adjusts the first polarizing assembly **104** in spatial relation to the pole tip assembly **102**. Similarly, a plurality of jack screws **7***b* (see FIGS. **3-6**) are adjustable in a manner that adjusts the second polarizing assembly **106** in spatial relation to the pole tip assembly **102**. These spatial relation adjustments provide both transverse and axial adjustments as will be explained in more detail below. Optional shims **9** can be used to maintain spacings **110**, **112**, respectively, between the first polarizing assembly **104** and the pole tip assembly **102** and between the second polarizing assembly **106** and the pole tip assembly **102**. A plurality of access ports **10** in the flux return center section **11** of the pole tip assembly **102** provide access from the exterior of the pole tip assembly **102** to the space **103** (see FIG. **5**) between interfacing pole piece tips **1***a*, **1***b* inside the pole tip assembly **102**, e.g., for inserting magnetic flux sensing tools and measurement samples into that space **103**.

With reference now primarily to FIGS. **4** and **5**, the first polarizing assembly **104** comprises a first permanent magnet unit **114**, which, in the example magnet assembly **100**, comprises a first disk magnet **3***a* and a plurality of first magnet sectors **4***a* arranged as a first ring magnet structure **101** (see FIG. **7**). The first disk magnet **3***a* is axially magnetized in one axial direction as indicated by the axial flux arrow **116**, and the magnet sectors **4***a* are magnetized radially outward as indicated by the radial flux arrows **118**. Similarly, the second polarizing assembly **106** comprises a second permanent magnet unit **120**, which, in the example magnet assembly **100**, comprises a second disk magnet **3***b* and a plurality of second magnet sectors **4***b* arranged as a second ring magnet structure **105** (see FIG. **9**). The second disk magnet **3***b* is axially magnetized in the same axial direction as the first disk magnet **3***a* as indicated by the axial flux arrow **122**, and the magnet sectors **4***b* are magnetized radially inward as indicated by the radial flux arrows **124** in FIGS. **4** and **5**.

Referring now primarily to FIG. **5**, a first pole piece **130** in the example magnet assembly **100** comprises a first pole piece body **2***a* in the first polarizing assembly **104** and a first pole piece tip **1***a* in the pole tip assembly **102**. Similarly, a second pole piece **132** in the example magnet assembly **100** comprises a second pole piece body **2***b* in the second polarizing assembly **106** and a second pole piece tip **1***b* in the pole tip assembly **102**. The first pole piece tip **1***a* and the second pole piece tip **1***b* are mounted in the pole tip assembly **102** in immovable, facing relation to each other with a fixed space **103** between them. Accordingly, with the first pole piece body **2***a* mounted in the first polarizing assembly **104**, the second pole piece body **2***b* mounted in the second polarizing assembly **106**, and the first and second pole piece tips **1***a*, **1***b* mounted in the pole tip assembly **102**, the first pole piece tip **1***a* is adjustably moveable along with the pole tip assembly **102** in spatial relation to the first pole piece body **2***a*, and the second pole piece tip **1***b* is adjustably moveable along with the pole tip assembly **102** in spatial relation to the second pole piece body. In other words, the pole tip assembly **102**, including the first pole piece tip **1***a* and the second pole piece tip **1***b*, is adjustably moveable in relation to both the first polarizing assembly **104** and the second polarizing assembly **106**, while the first and second pole piece tips **1***a*, **1***b* are immovable in fixed spatial relation to each other with the fixed space **103** between them. A cylindrical first flux return **6***a* encloses the first polarizing assembly **104**, except on the interior end of the first polarizing assembly **104** that faces the pole tip assembly **102**, and a cylindrical second flux return **6***b* encloses the second polarizing assembly **106**, except on the interior end of the second polarizing assembly **106** that faces the pole tip assembly **102**. A ring-like flux return center section **11** surrounds the periphery of the pole tip assembly **102**. Accordingly, the magnetic flux emanating from the first and second permanent magnet units **114**, **120** is guided efficiently from one end of the magnet assembly **100** to the other by the first flux return **6***a*, the flux return center section **11**, and the second flux return **6***b*, as indicated by the flux return arrows **138**, while minimizing stray flux outside the magnet assembly **100**.

The magnetic forces of the first permanent magnet unit **114** and the second permanent magnet unit **120** hold the first polarizing assembly **104**, the pole tip assembly **102**, and the second polarizing assembly **106** strongly and tightly together. The three jack screws **7***a* in the first polarizing assembly **104** extend through, and are threaded in, holes **140** in the first flux return **6***a* of the first polarizing assembly **104**, thus can be screwed individually against the pole tip assembly **102** to adjustably move the first polarizing assembly **104** and the pole tip assembly **102** spatially apart from each other. Therefore, screwing the jack screws **7***a* against the pole tip assembly **102** moves the first pole piece body **2***a* and the first pole piece tip **1***a* spatially apart from each other. As shown in FIGS. **1** and **2**, the plurality of jack screws **7***a* (three jack screws **7***a* in the example magnet assembly **100** shown in FIGS. **1-8**) are spaced angularly apart from each other with respect to the longitudinal axis **142** of the magnet assembly **100** so that jack screws **7***a* can be screwed inwardly or outwardly against the pole tip assembly **102** in amounts and in combinations that enable movement of the first polarizing assembly **104** in relation to the pole tip assembly **102** axially along the longitudinal axis **142**, rotationally about a first orthogonal vertical axis **144**, or rotationally about a first orthogonal horizontal axis **146** (see FIGS. **1** and **6**), or any combination of those movements. Therefore, such adjustments of the jack screws **7***a* also result in corresponding movement of the first pole piece body **2***a* in relation to the first pole piece tip **1***a* along the longitudinal axis **142**, rotationally substantially about the first orthogonal vertical axis **144**, or rotationally substantially about the first orthogonal horizontal axis **146**, or any combination of those movements, which thereby adjust the gradients of the magnetic field to improve field homogeneity in the space **103** between the first pole piece tip **1***a* and the second pole piece tip **1***b*.

Similarly, the three jack screws **7***b* in the second polarizing assembly **106** (see FIGS. **5**, **6**, and **9**) extend through, and are threaded in, holes **150** in the second flux return **6***b* of the second polarizing assembly **106**, thus can be screwed individually against the pole tip assembly **102** to adjustably move the second polarizing assembly **106** and the pole tip assembly **102** spatially apart from each other. Therefore, screwing the jack screws **7***b* against the pole tip assembly **102** moves the second pole piece body **2***b* and the second pole piece tip **1***b* spatially apart from each other. The plurality of jack screws **7***b* (three jack screws **7***b* in the example magnet assembly **100** shown in FIGS. **1-8**) are spaced angularly apart from each other with respect to the longitudinal axis **142** of the magnet assembly **100**, similar to the angular spacing of the jack screws **6***a*, so that jack screws **7***b* can be screwed inwardly or outwardly against the pole tip assembly **102** in amounts and in combinations that enable movement of the second polarizing assembly **106** in relation to the pole tip assembly **102** along the longitudinal axis **142**, rotationally about a second orthogonal vertical axis **154**, or rotationally about a second orthogonal horizontal axis **156**, or any combination of those movements. Therefore, such adjustments of the jack screws **7***b* also result in corresponding movement of the second pole piece body **2***b* in relation to the second pole piece tip **1***b* along the longitudinal axis **142**, rotationally about the second orthogonal vertical axis **154**, or rotationally about the first orthogonal horizontal axis **156**, or any combination of those movements, which thereby adjust the gradients of the magnetic field to improve field homogeneity in the space between the first pole piece tip **1***a* and the second pole piece tip **1***b*.

As mentioned above, access ports **10** are provided to enable flux measuring instrumentation or samples to be measured or analyzed (not shown) to be inserted into the space **103** between the first and second pole piece tips **1***a*, **1***b* inside the magnet assembly **100** for measuring the magnetic gradient in that space **103** as the adjustments with the jack screws **7***a*, **7***b* are made. As an option, to hold the adjusted spacings between the first polarizing assembly **104** and the pole tip assembly **102**, or between the second polarizing assembly **106** and the pole tip assembly **102**, one or more shims **9** can be positioned in those spaces. With such shims **9** in such positions, the jack screws **7***a*, **7***b* can be backed away from the pole tip assembly **102**, and the magnetic force between the first polarizing assembly **104**, the pole tip assembly **102**, and the second polarizing assembly **106** press those components tightly on the shims **9** and hold the shims **9** in those positions.

Two of the four access ports **10** providing access to the space **103** in the center of the magnet assembly **100** and four of the six shims **9** used for adjustment can be seen in FIG. **1**. Some components of the example magnet assembly **100**, including the pole piece tips **1***a*, **1***b* and the pole piece bodies **2***a*, **2***b*, have rotational symmetry about the longitudinal axis **142**. Other embodiments may be rotationally asymmetric. Some components in the example magnet assembly **100** embodiment have a reflection symmetry about the plane of section plane **8-8**. Other embodiments may lack this reflection symmetry.

The pole piece tips **1***a*, **1***b* can be made of soft magnetic material which is saturated in some regions. In the example magnet assembly **100** embodiment, the pole piece tips **1***a*, **1***b* are made of the iron-cobalt alloy known as permendur, but in other embodiments the pole piece tips **1***a*, **1***b* may be made of iron, steel, or of other soft magnetic material. Also in other embodiments, the pole piece tips **1***a*, **1***b* may be unsaturated everywhere. The pole piece tips **1***a*, **1***b* are rigidly supported by the pole tip mount **5** with the respective flat, circular faces **160**, **162** of the pole piece tips **1***a*, **1***b* substantially parallel to each other and coaxial with each other, for example, on the longitudinal axis **142**. In other embodiments the pole piece tip faces **160**, **162** may be non-planar with a reflection symmetry plane between the faces. The pole tip mount **5** is made from a substantially non-magnetic material such as aluminum, titanium, or a ceramic. The four access ports **10** are provided in both the flux return center section **11** and in the pole mount **5** so that samples or other measurement apparatus can be moved into the space **103** in the center of the magnet assembly **100** between the two pole piece tip faces **160**, **162**. In other embodiments at least one access port is provided. In FIG. **2** the very ends of the pole piece tips **1***a*, **1***b* can be seen through the access ports **10** and pole tip mount **5**, but this may not be the case in other embodiments. The pole mount **5** is a single piece that only appears split into two parts in FIGS. **5**, **6**, and **8** because the plane of these figures includes the access ports. In other embodiments the pole tip mount **5** can be formed from a plurality of parts, so long as the pole piece tips **1***a*, **1***b* and pole mount **5** together comprise a rigid assembly. The pole piece tips **1***a*, **1***b*, the pole mount **5**, and the flux return center section **11** together form a rigid pole tip assembly **102**. The pole tip assembly **102** can be constructed with the poles piece tips **1***a*, **1***b* accurately coaxial and parallel while in unmagnetized condition so that magnetic forces do not complicate manufacturing.

The remainder of the example magnet assembly embodiment **100** shown in FIGS. **1-9** is comprised of the two similar polarizing assemblies **104**, **106**, which are nearly mirror images of one another, but differ in the directions of the magnetizations of their permanent magnet components as explained above. The first polarizing assembly **104** comprises the first pole piece body **2***a*, the first permanent magnet sectors **4***a*, the first disk magnet **3***a*, the first flux return **6***a*, the first jack screws **7***a*, and the first center bolt **8***a*, while the second polarizing assembly is comprised of the second pole piece body **2***b*, the second permanent magnet sectors **4***b*, the second magnet disk **3***b*, the second flux return **6***b*, the second jack screws **7***b*, and the second center bolt **8***b*.

The pole piece bodies **2***a*, **2***b* in the example magnet assembly **100** can be made of permendur soft magnetic material. In other embodiments the pole piece bodies **2**_a_, **2**_b_ may be made of iron, steel, or other soft magnetic materials. The pole piece bodies **2**_a_, **2**_b_ contain tapped holes on axis **142** for bolts **8**_a_, **8**_b_. These bolts **8**_a_, **8**_b_ are used to hold the pole piece bodies **2**_a_, **2**_b_, respectively, in place against magnetic forces during construction of each polarizing assembly **104**, **106** and in the final assembly. In other embodiments other means may be used for such securement.

A plurality of permanent magnet sectors **4**_a_, **4**_b_ comprise ring magnets **101**, **105**, respectively (see FIGS. **7** and **9**), with substantially radially directed magnetization as explained above. In the illustrated embodiment each ring magnet **101**, **105** is comprised of 12 magnet sectors **4**_a_, **4**_b_, respectively, and each magnet sector **4**_a_, **4**_b_ can be made of the hard magnetic material NbFeB. In other embodiments different numbers of magnet sectors may be used, or each ring magnet may be constructed from a single permanent magnet with radial magnetization. In other embodiments the permanent magnet material may be NeFeB, SmCo, other rare-earth ceramic material or other permanent magnet material.

Each polarizing assembly **104**, **106** comprises an axially magnetized disk magnet **3**_a_, **3**_b_, respectively, which can be made of the hard magnetic material NdFeB. In other embodiments the disk magnets **3**_a_, **3**_b_ may be made of NeFeB, SmCo, other rare-earth ceramic material or other permanent magnet material. Each disc magnet **3**_a_, **3**_b_ has a hole **164**, **166**, respectively, along the central axis **142** to clear the central bolts **8**_a_, **8**_b_. In other embodiments where other means are used for such securement, these holes may be absent, or additional holes may be present.

Each polarizing assembly **104**, **106** is enclosed by the respective flux returns **6**_a_, **6**_b_. Persons skilled in the art will understand that the flux return center section **11** also functions as a part of the entire flux return, and that the purpose of the entire flux return is to guide magnetic flux efficiently from one end of the magnet assembly to the other, while minimizing stray flux outside the magnet assembly **100**. The flux returns **6**_a_, **6**_b_ can be made of low carbon steel, a soft magnetic material, but may be made of iron or other soft magnetic material in other embodiments. The flux returns **6**_a_, **6**_b_ may be comprised of separate pieces to facilitate magnet assembly.

In FIGS. **4**-**7** and **9**, the arrows indicate the direction of magnetization of the permanent ring and disk magnets. In the first polarizing assembly **104**, the ring magnet **101** magnetization is radially outwards as indicated by arrows **118**, while the disk magnet **3**_a_ magnetization is axial and directed away from the pole tip assembly **102** as indicated by the arrow **116**. In the second polarizing assembly **106**, the ring magnet **105** magnetization is radially inwards as indicated by the arrows **124**, while the disk magnet **3**_b_ magnetization is axial and directed towards the pole tip assembly **102** as indicated by the arrow **122**. Persons skilled in the art will recognized that polarizing assemblies with these magnetization directions will draw flux out of the pole tip assembly **102** on its left side, and insert flux into the pole tip assembly **102** on its right side, such that an intense and substantially uniform magnetic field directed to the left will be created in the space **103** between the pole tip faces **160**, **162**. Persons skilled in the art will also understand that the entire flux return **6**_a_, **11**, **6**_b_ will guide flux from the left side of the magnet assembly **100** back to the right side, and that reversing the direction of all magnetization will only change the direction of the intense field between the pole tip faces **1**_a_, **1**_b_.

FIG. **8** is section plane **8**-**8** in FIG. **2** along the central radial plane of the magnet assembly **100**. The very end of the pole piece tip **1**_b_ is protruding out of the pole piece tip mount **5**. The channels in the pole piece tip mount **5** that allow access to the space **103** in the center of the magnet assembly **100** are now visible and form a cross around the pole piece tip **1**_b_. Beyond the pole tip mount **5**, the ring magnet **101** sectors **4**_b_ can be partially seen.

FIG. **7** shows a view in the axial direction of the first ring magnet **101** of the first polarizing assembly **104**. In the example magnet assembly **100** embodiment, the first ring magnet comprises twelve (12) first sectors **4**_a_, each with substantially uniform magnetization. Also shown in FIG. **7** are the first pole piece body **2**_a_ and the first flux return **6**_a_.

FIG. **9** shows a view in the axial direction of the second polarizing assembly **106**. In this example magnet assembly **100** embodiment, the second ring magnet **105** comprises twelve (12) second sectors **4**_b_, each with substantially uniform magnetization. Also shown in FIG. **9** is the second pole piece body **2**_b_ and the second flux return **6**_b_.

The example magnet assembly **100** comprises two polarizing assemblies **104**, **106** and one pole tip assembly **102**. These components are each rigid and stable assemblies that may be constructed separately. To provide adjustment of the field gradients, shims **9** and jack screws **7**_a_, **7**_b_ are provided as means to adjust the positions of each polarizing assembly **104**, **106** in relation to the pole tip assembly **102**. FIGS. **1** and **3** show three jack screws **7**_a_ and three shims **9** in a tripod configuration, i.e., space angularly 120 degrees from each other in relation to the longitudinal axis **142**. Other embodiments can have a different number of jack screws and shims. Contact between the pole tip assembly **102** and each polarizing assembly **104**, **106**, respectively, occurs only at the shims **9** and at the tips of the jack screws **7**_a_, **7**_b_. A gap is provided between the pole piece tip **1**_a_ and the pole piece body **2**_a_, and a similar gap is provided between the pole tip **1**_b_ and pole piece body **2**_b_, so that the pole piece tips **1**_a_, **1**_b_ are not in contact with the respective adjacent pole piece bodies **2**_a_, **2**_b_. The jack screws are used to slightly separate the flux returns **6**_a_, **6**_b_ from the flux return center section **11** as shown by the gaps **110** and **112** in FIG. **1**, so that shims **9** of various thicknesses can be inserted or removed. Strong attractive axial magnetic forces are present when the three assemblies **102**, **104**, **106** are brought together, so that the whole forms a rigid assembly.

The jack screws **7**_a_, **7**_b_ and shims **9** can be used to adjust the magnetic field gradients. For one example, if the first polarizing assembly **104** is slightly withdrawn by increasing the thickness of all three shims **9**, thus the gap **110**, between the first polarizing assembly **104** and the pole tip assembly **102**, the gap between the first pole piece tip **1**_a_ and the first pole piece body **2**_a_ will increase, thus reducing the power of the first polarizing assembly **104** to withdraw flux from the pole tip assembly **102**. Thus the magnetic field in the space **103** between the pole piece tip faces **160**, **162** will tend to be stronger on the right side than on the left side of the space **103** and a gradient in the axial direction increasing to the right will be created. For another example, if the shim **9** at the top of FIG. **4** between the first polarizing assembly **104** and the pole tip assembly **102** is made thicker, the first pole piece body **2**_a_ will tilt, thus change the shape of the gap **110**, so that the first pole piece body **2**_a_ will be less effective at withdrawing flux from the top side of the pole tip assembly **102**, and a transverse gradient increasing toward the bottom of the space **103** between the pole tip faces **160**, **162** will be created. Similarly, adjustments to the size and shape of the gap **112** between the second pole piece body **2**_b_ and the pole tip assembly **102** by adjusting the jack screws **7***b*, which also affect the axial or transverse gradients or both in the space **103** between the pole tip faces **160**, **162**.

Gradient adjustments made as described above are much less sensitive than gradient adjustments made by changing the relative positions of the two pole piece faces **160**, **162**. For example, for the embodiment illustrated in FIG. **4**, the sensitivity of transverse gradients to tilt or lack of parallelism between the first pole piece tip **1***a* and the first pole piece body **2***a* or between the second pole piece tip **1***b* and the second pole piece body **2***b* is about 30 times less than the sensitivity to tilt or lack of parallelism between the pole tip faces **160**, **162**.

In the example magnet assembly **100** shown FIGS. **1-9** and described above, each polarizing assembly **104**, **106** comprises both axially and radially magnetized permanent magnet material, a soft magnetic pole piece body, and soft magnetic flux return. This particular arrangement of soft and hard magnetic materials is not essential to the disclosed invention. Many other arrangements of hard and soft magnetic material can be used to withdraw flux from one side of the pole tip assembly **102** and insert it into the other side of the pole tip assembly **102**.

In the example magnet assembly **100** shown in FIGS. **1-9**, a portion of the flux return, i.e., the flux return center section **11**, is included in the pole piece tip assembly **102**, but this is not an essential feature of the disclosed invention. Alternately the flux returns **6***a* and **6***b* could be extended to meet one another and there could be no part of the flux return in the pole tip assembly. In such an alternative embodiment, the jack screws **7***a*, **7***b* would bear against the opposite flux return **6***a*, **6***b*, respectively, or against opposing jack screws **7***a*, **7***b*, or one set of the jack screws in one of the polarizing assemblies **106**, for example, the jack screws **7***b* in the second polarizing assembly **106**, could be eliminated, or vice versa. Also, in such an alternative embodiment, the optional shims **9** would then be positioned between the first flux return **6***a* and the second flux return **6***b*.

In the example magnet assembly **100** embodiment shown in FIGS. **1-9**, jack screws and shims are used to control the relative positions between the polarizing assemblies **104**, **106** and the pole tip assembly **102**. Other adjusting means for adjusting and controlling these positions can be used.

The example magnet assembly **100** and the associated improved field homogeneity are of particular value at fields above 2 Tesla, where the pole tips are partly or fully saturated. However, the magnet assembly described above can also be used advantageously at lower fields to improve homogeneity.

Other alternative embodiments are also possible. For example, the pole piece bodies **2***a*, **2***b* could be eliminated, and the respective pole piece tips **1***a*, **1***b* could be extended to very close proximity to the respective disk magnets **3***a*, **3***b*. In another embodiment, the pole piece bodies **2***a*, **2***b* could be eliminated and replaced, for example, with disk magnets. In each of such alternatives, as in the example magnet assembly **100** described above, the spacing **103** between the first and second pole piece tips **1***a*, **1***b* remains the same and is not changed when adjustments are made in either the spacing between the first polarizing assembly **104** and the first pole tip **1***b* or the spacing between the second polarizing assembly **106** and the second pole tip **1***b* to adjust the magnetic field gradients in the space between the pole piece tips **1***a*, **1***b*.

The description above illustrates several advantages provided by the example magnet assembly **100**, including the following: (a) The pole tips are combined into an assembly that rigidly and permanently fixes the relative position of the two poles tips, which makes the most critical dimensions in the disclosed magnet design stable over time and able to survive mechanical shocks; (b) The pole tip assembly is not subject to magnetic forces when it is manufactured, making it easier to achieve and verify the high mechanical tolerances that are required; (c) Field gradients are adjusted by changing the relative position between the pole tip assembly and two polarizing assemblies, and these adjustments are much less sensitive than corresponding adjustments of the relative positions of the two pole tips, which makes them very stable over time and more able to survive mechanical shock; (d) The disclosed gradient adjusting means can be used in the completed magnet assembly while the field inhomogeneity is being measured; (e) The disclosed gradient adjusting means can be advantageously used with saturated or unsaturated pole tips; and (f) The disclosed gradient adjusting means can be advantageously used with polarizing assemblies containing axially and radially magnetized permanent magnets, or only axially polarized magnets, or other configurations of permanent magnets.

Accordingly, resort may be made to all suitable combinations, subcombinations, modifications, and equivalents that fall within the scope of the invention as defined by the features. The words "comprise," "comprises," "comprising," "include," "including," and "includes" when used in this specification, including the claims, are intended to specify the presence of stated features, integers, components, or steps, but they do not preclude the presence or addition of one or more other features, integers, components, steps, or groups thereof. Directional terms used in this description, including, for example, left, right, vertical, horizontal, top, bottom, and the like are with reference to the orientation of the magnet assembly **100** in the drawing sheets, not with regard to any particular orientation of the magnet assembly **100** in actual use.

What is claimed is:

1. A permanent magnet assembly comprising:

(a) a pole tip assembly comprising two pole tips of magnetic material, disposed symmetrically with respect to a mirror plane between them, and a pole tip mount of rigid material, whereby said pole tips and pole tip mount together comprise a rigid assembly,

(b) a first polarizing assembly comprising permanent magnets disposed to draw magnetic flux out of a first side of said pole tip assembly, and an enclosing magnetic flux return disposed to guide flux into a second polarizing assembly,

(c) said second polarizing assembly comprising permanent magnets disposed to insert magnetic flux into a second side of said pole tip assembly, and an enclosing magnetic flux return disposed to guide flux out of said first polarizing assembly,

(d) adjusting means whereby the position of said first polarizing assembly and the position of said second polarizing assembly can be adjusted relative to the position of said pole tip assembly,

whereby said adjusting means improves the homogeneity of the magnetic field in the region between said symmetrically disposed pole tips.

2. The permanent magnet of claim **1** wherein said first and second polarizing assemblies comprise axially magnetized permanent magnets.

3. The permanent magnet of claim **1** wherein said first and second polarizing assemblies comprise axially magnetized permanent magnets and radially magnetized permanent magnets.

4. The permanent magnet of claim **1** wherein said pole tips are magnetically saturated in at least some regions.

5. Magnet apparatus, comprising:

a first magnet and a second magnet positioned adjacent to each other and aligned with each other in a manner that produces a magnetic flux along a longitudinal axis that extends through both the first magnet and the second magnet;

a first pole piece with a first pole piece face and a second pole piece with a second pole piece face, wherein the first pole piece and the second pole piece are positioned between the first magnet and the second magnet with the first pole piece face and the second pole piece face facing each other a spaced distance apart from each other in the magnetic flux along the longitudinal axis so that there is a space between the first pole piece face and the second pole piece face, and wherein there is a first gap between the first magnet and the first pole piece face and there is a second gap between the second magnet and the second pole piece face; and

adjusting means for adjusting the size or shape of the first gap or the second gap.

6. The magnet apparatus of claim **5**, wherein:

the first pole piece comprises a first pole piece body and a first pole piece tip, and the first gap is between the first pole piece body and the first pole piece tip; and

the second pole piece comprises a second pole piece body and a second pole piece tip, and the second gap is between the second pole piece body and the second pole piece tip.

7. The magnet apparatus of claim **5**, wherein the first pole piece tip and the second pole piece tip are fixed in immovable relation to each other so that the space between the first pole piece face and the second pole piece face is fixed in size and shape.

8. The magnet apparatus of claim **5**, wherein the first magnet is a permanent first magnet, and the second magnet is a permanent second magnet.

9. A method of providing a magnetic field, comprising:

creating a magnetic flux along an axis;

positioning a first pole piece comprising a first pole piece body and a first pole piece tip that has a first pole piece tip face in the magnetic flux with a first gap between the first pole piece body and the first pole piece tip;

positioning a second pole piece comprising a second pole piece body and a second pole piece tip that has a second pole piece tip face in the magnetic flux with a second gap between the second pole piece body and the second pole piece tip;

positioning the first pole piece and the second pole piece in the magnetic flux with the first pole piece tip face and the second pole piece face facing each other with a space between the first pole piece tip face and the second pole piece tip face; and

adjusting homogeneity of the magnetic flux in the space between the first pole piece tip face and the second pole piece tip face by varying the first gap or by varying the second gap or by varying both the first gap and the second gap.

10. The method of claim **9**, including varying the first gap by moving the first pole piece body in relation to the first pole piece tip.

11. The method of claim **9**, including varying the second gap by moving the second pole piece body in relation to the first pole piece tip.

12. The method of claim **10**, including varying the first gap by moving the first pole piece body along a longitudinal axis toward or away from the first pole piece tip.

13. The method of claim **10**, including varying the first gap by rotating the first pole piece body in relation to the first pole piece tip about an orthogonal axis.

14. The method of claim **11**, including varying the second gap by moving the second pole piece body along a longitudinal axis toward or away from the second pole piece tip.

15. The method of claim **11**, including varying the second gap by rotating the second pole piece body in relation to the second pole piece tip about an orthogonal axis.

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